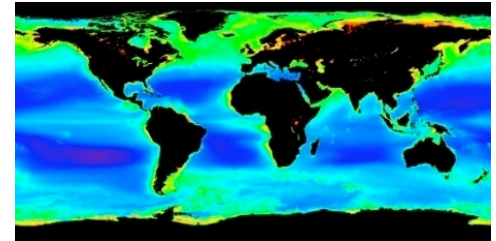


The Color of the Sea



And What It Means

Acknowledgements and Thanks!!

Mike Behrenfeld, Gene Feldman, Maureen Kennelly, Chuck McClain, Colleen Mouw, Jan Rines, Dave Siegel, Venetia Stuart, and Toby Westberry.

International Ocean Colour Coordinating Group,
NASA Headquarters, University of Rhode Island
and Woods Hole Oceanographic Institution

Outline

- What is “ocean color”? Introduction to ocean color radiometry (OCR).
- OCR joins Earth System Science – impact of first basin scale image (*Atlantic spring bloom*).
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- New developments
- Conclusions



Alvin



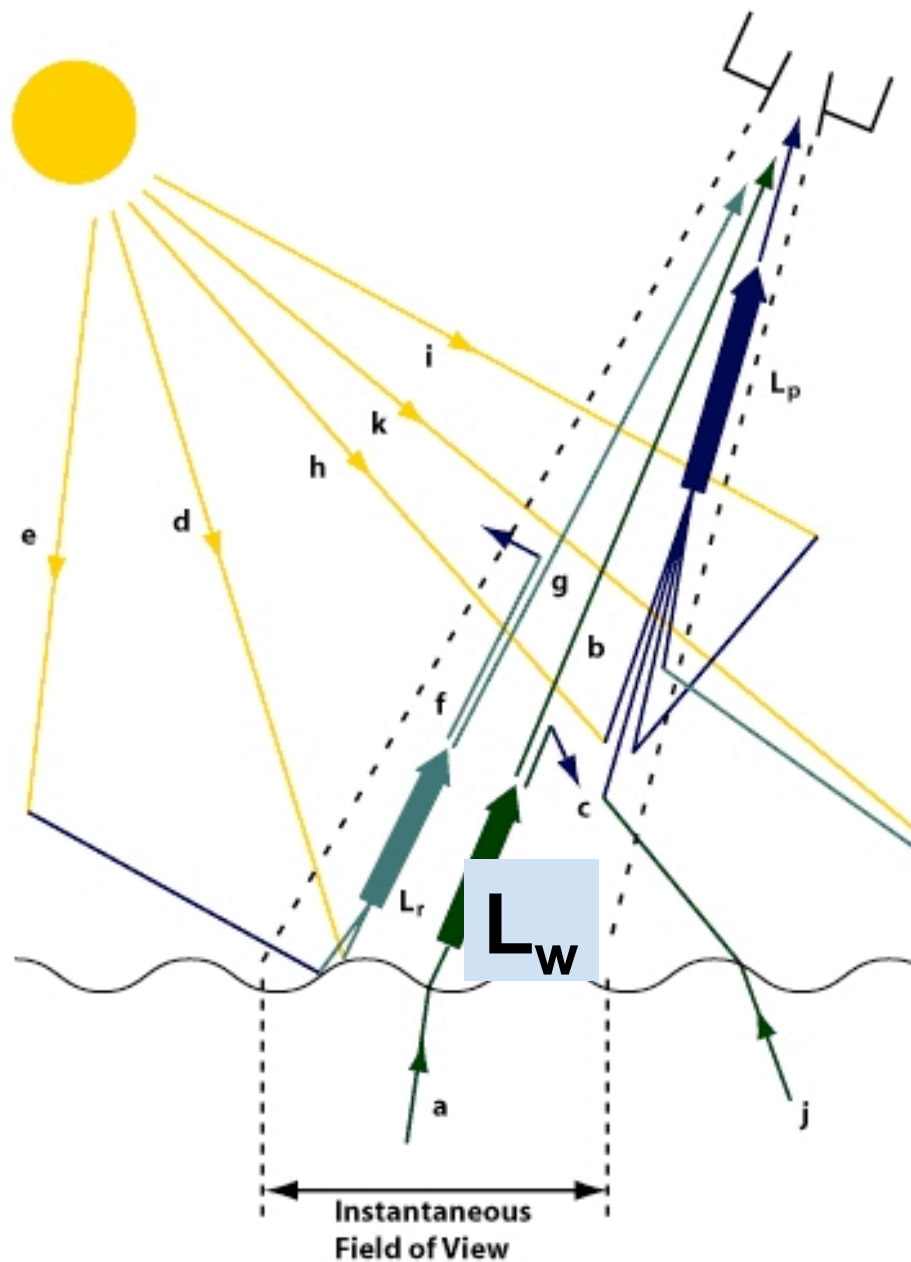
QE3



Marine Phytoplankton
(Diatoms)
Ca. 200X mag.

Photos by Dr. Jan
Rines, GSO/URI





Pathlengths to a Satellite Sensor for Sunlight Shining on the Sea

L_w = water leaving radiance which contains the information on in-water constituents such as phytoplankton concentration.

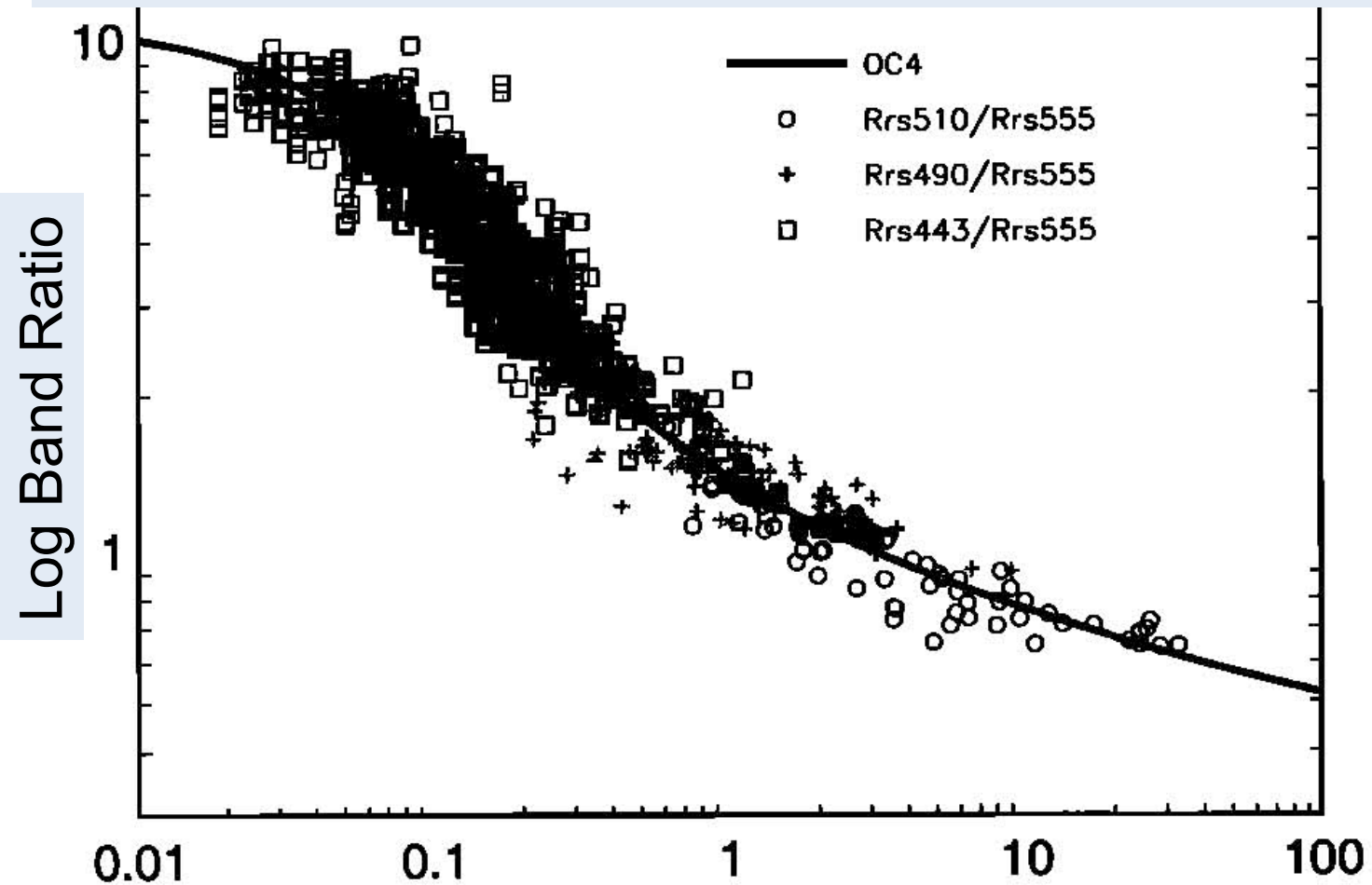
However, most of the signal reaching the sensor has been affected by scattering and absorption in the atmosphere. S/N = about 0.1 on average for key wavelengths.

Sensor Wavelengths for SeaWiFS – which is in polar orbit,
crossing equator at local noon, 1 km pixel resolution,
1500-2800 km swath width

Band Number	Wavelength (nm)	Purpose
1	402-422	Colored Organic Matter
2	433-443	Phytoplankton Pigments
3	480-490	Phytoplankton Pigments
4	500-520	Phytoplankton Pigments
5	545-565	Back Scatter - Particulate Carbon
6	660-680	CZCS Heritage and Back Scatter
7	745-785	Atmospheric Correction
8	845-885	Atmospheric Correction

SeaWiFS OC-4 Band Ratio Algorithm

(O'Reilly et al. 1998)



Log Phytoplankton Chlorophyll Concentration (mg m⁻³)

Outline

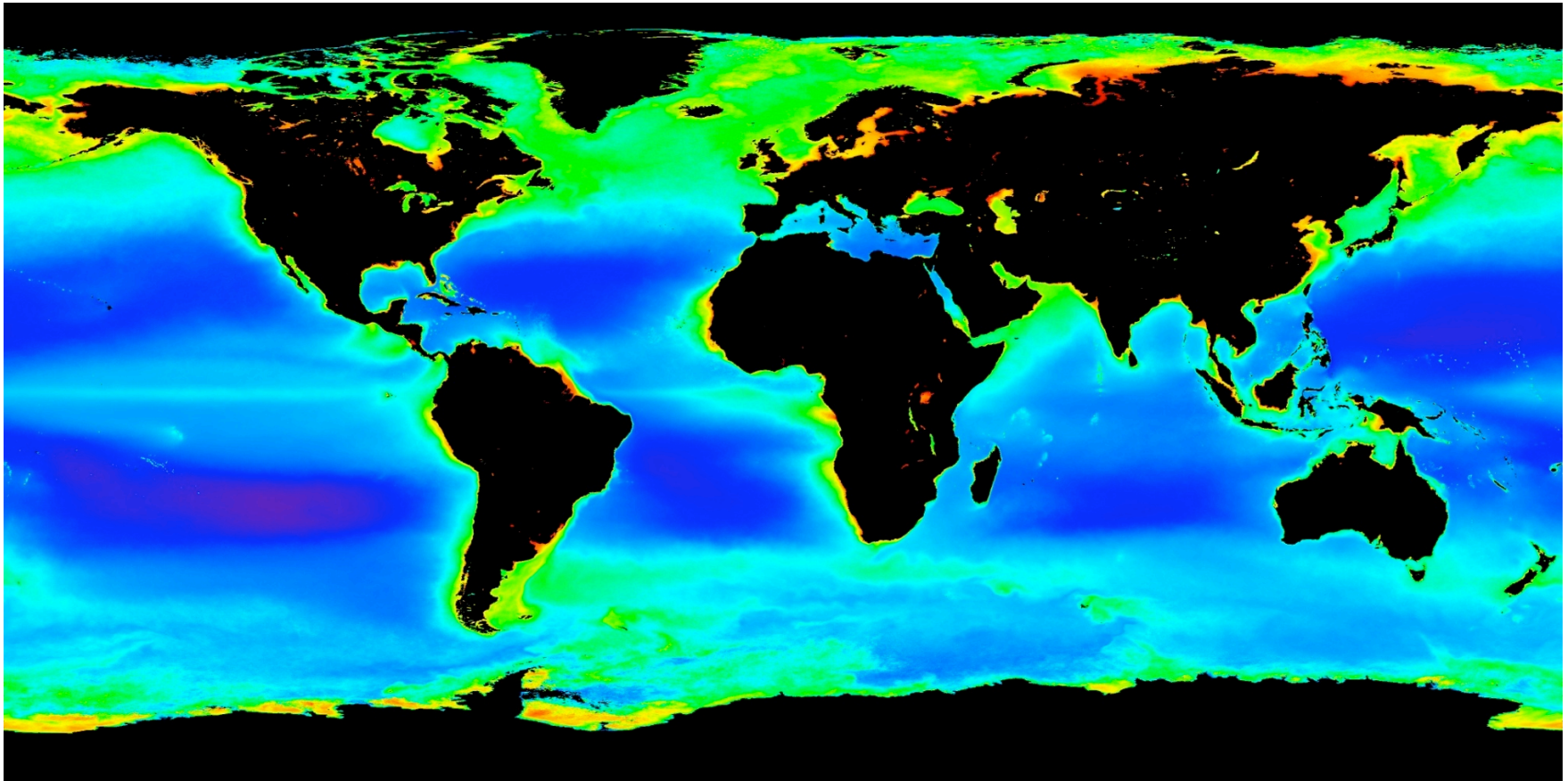
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OCR Joins Earth System Science



Courtesy of G. Feldman, NASA-GSFC

Composite SeaWiFS Chlorophyll Image: 1997-2009 (G. Feldman, NASA-GSFC)



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¹⁴C Database Approach (from Boss and Siegel)

Date	Author	NPP (Pg y ⁻¹)	Method
1952	Steemann Nielsen	20	few ¹⁴ C measurements
1957	Fleming & Laevastu	20	FAO production data (O ₂ , ¹⁴ C, etc)
1957	Steemann Nielsen	20-25	few ¹⁴ C measurements
1958	Fogg	32	FAO production data (O ₂ , ¹⁴ C, etc)
1968	Koblentz-Mishke <i>et al.</i>	23	Synthesis of many ¹⁴ C stations
1969	Bogorov	25	Synthesis of many ¹⁴ C stations
1969	Ryther	20	¹⁴ C & spatial model
1970	Koblentz-Mishke <i>et al.</i>	25-30	revision of '68 paper
1975	Platt & Subba Rao	31	new ¹⁴ C synthesis
1985	Shushkina	56	new ¹⁴ C & biomass data
1987	Martin <i>et al.</i>	51	revision of Koblentz-Mishke <i>et al.</i>
1989	Berger <i>et al.</i>	27	new ¹⁴ C synthesis

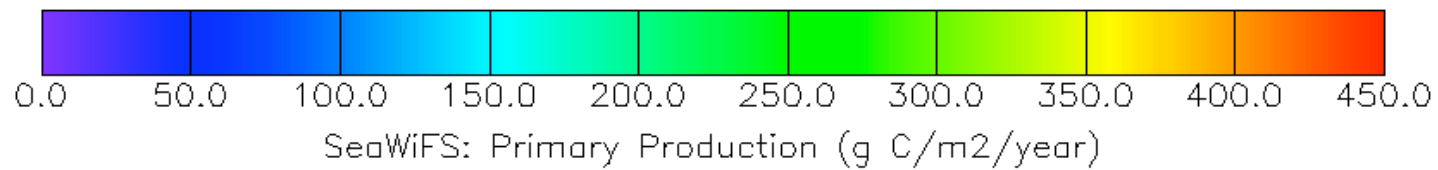
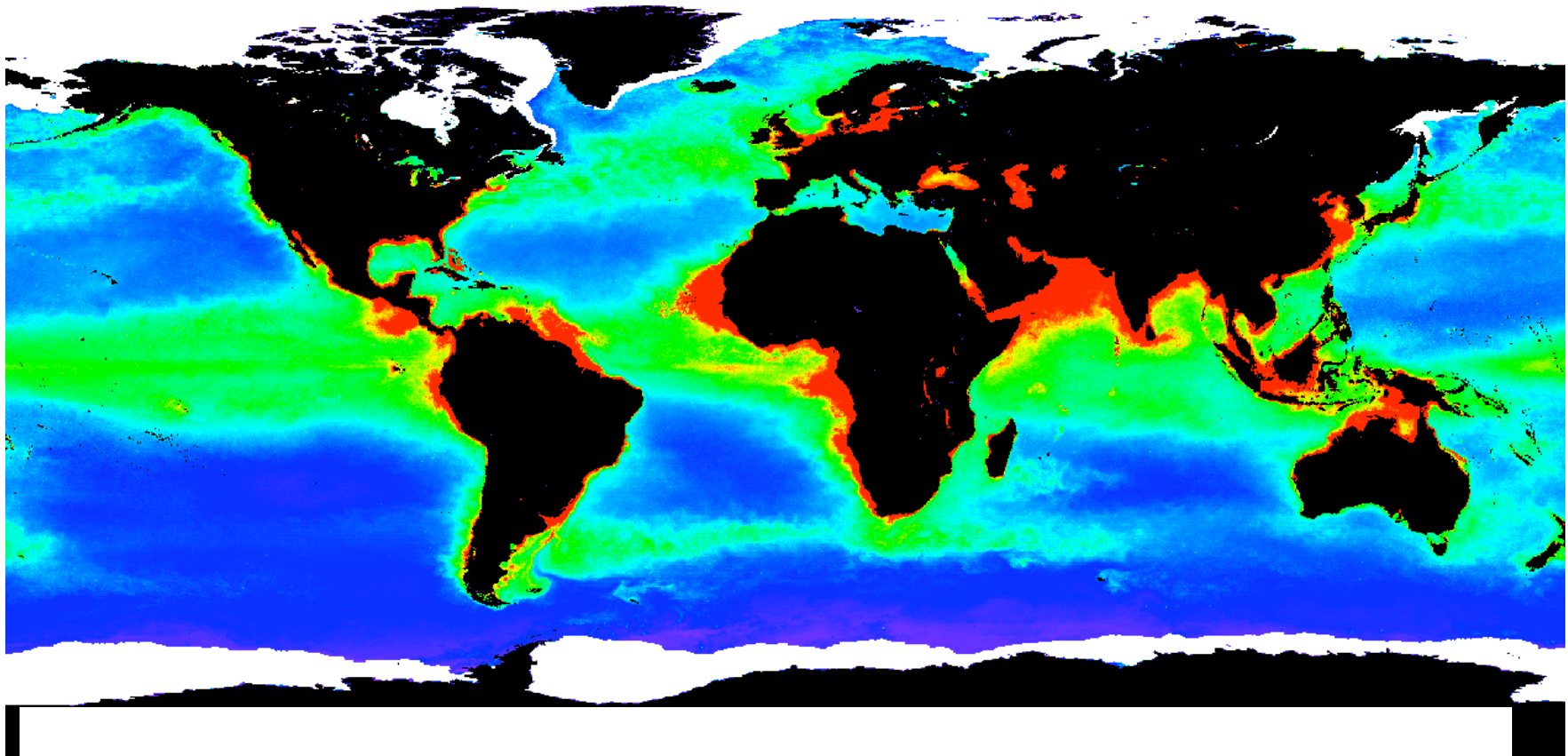
NPP calculations by many investigators based on satellite OCR measurements are generally higher ranging from ca. 40 to 50+ Pg y⁻¹

Calculating Net Primary Production (NPP) Using OCR Imagery Common Approach (since 1980s)

$$NPP \sim [Chl] \times Physiology \text{ (Temperature, Other)} \times Light$$

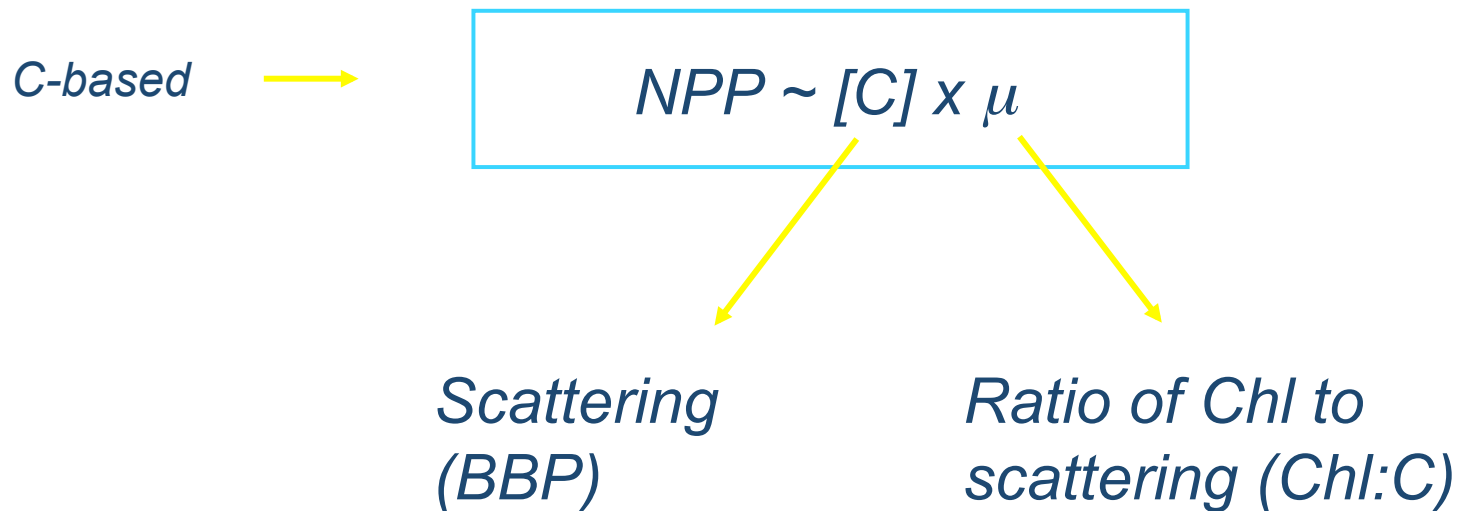
Phytoplankton chlorophyll	OCR
Incident solar irradiance (sunlight)	OCR or other satellite
Water clarity (sunlight vertical distribution)	OCR
Sea Surface Temperature (for physiology)	AVHRR, MODIS
Depth of the mixed layer	Numerical models, other
Physiology linking NPP to above variables	Literature/ <i>In situ</i> data bases

Vertically Generalized Production Model (VGPM) to Calculate NPP (Behrenfeld and Falkowski, 1997)

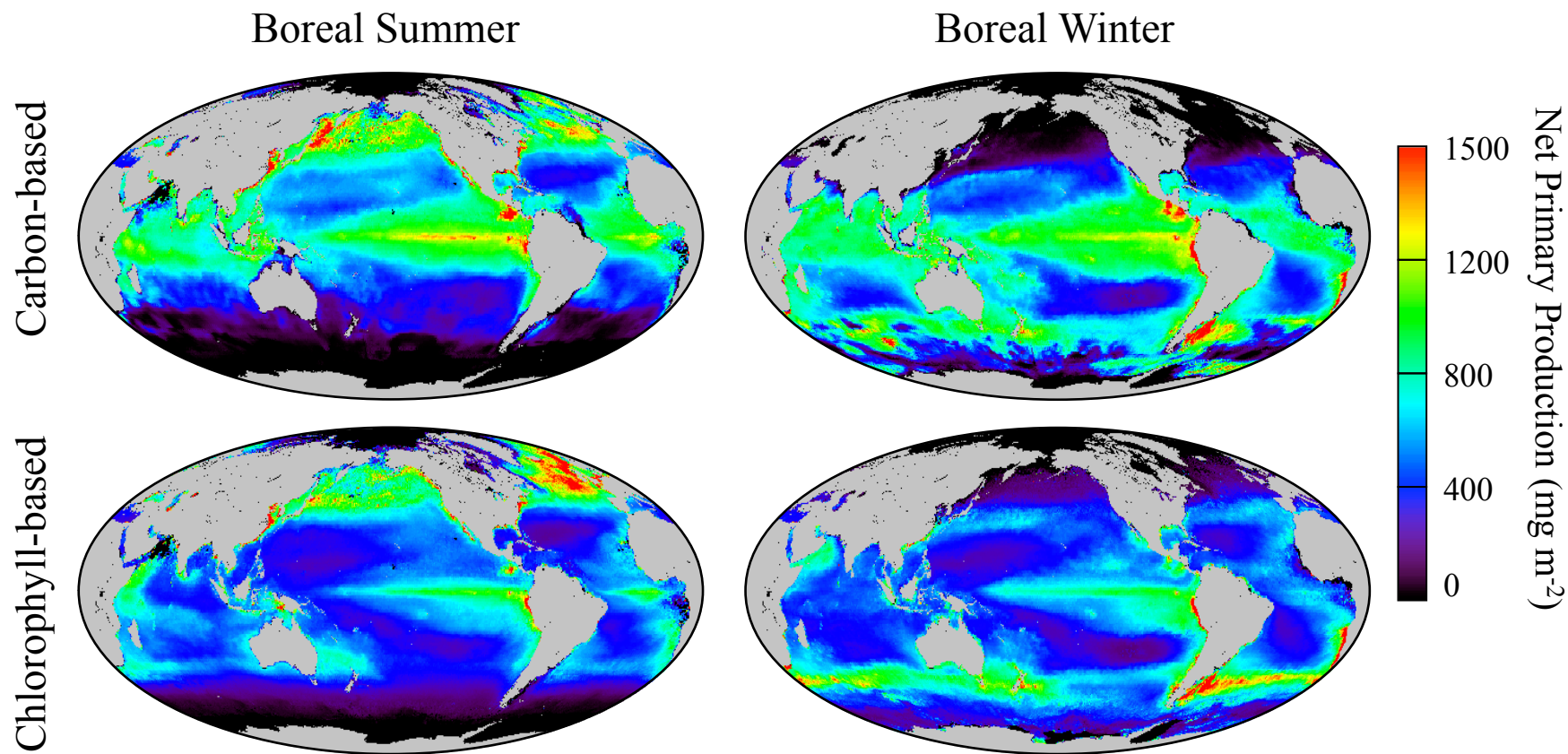


Calculating Net Primary Production (NPP) Using OCR Imagery

New Approach (Using GSM Inversion Products)



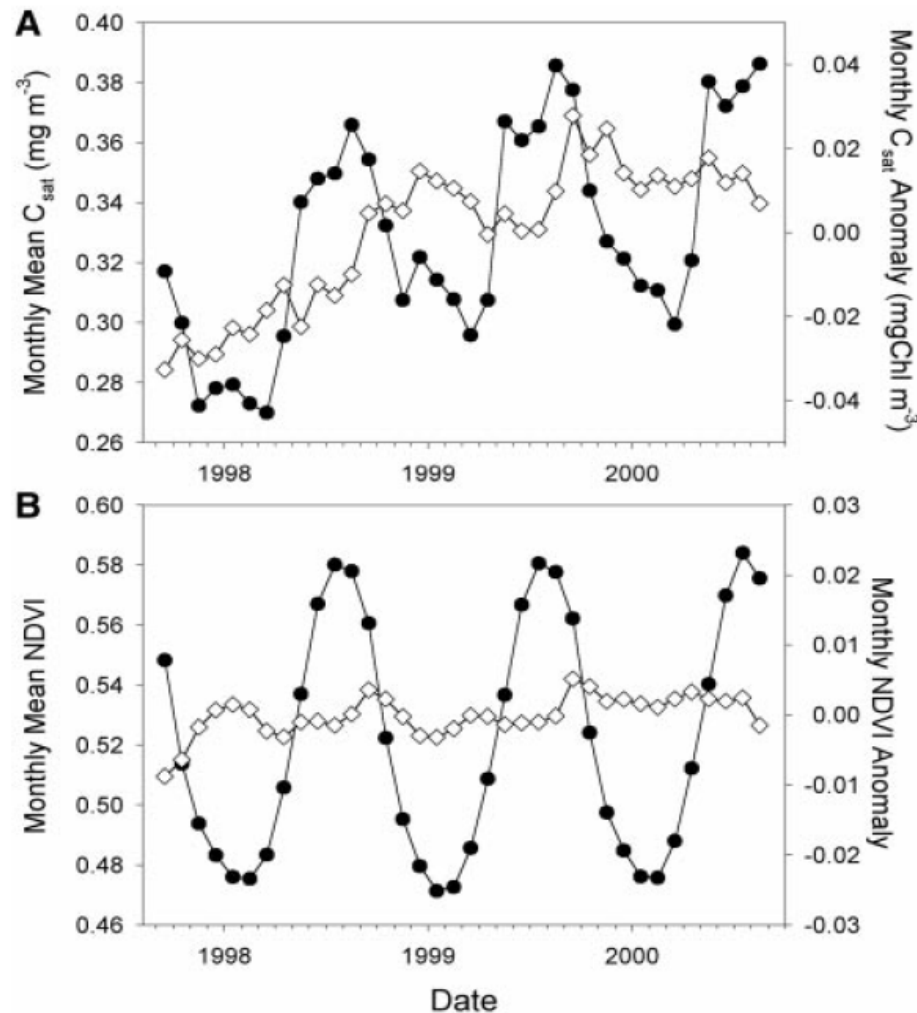
Phytoplankton Carbon	OCR (from backscatter)
Phytoplankton Growth Rate	OCR for physiology (C:Chl ratio)
Phytoplankton “State”	MODIS chlorophyll fluorescence bands



Slide courtesy of M. Behrenfeld

Biospheric NPP During ENSO Transition: Global monthly means (●) and anomalies (◇)

SeaWiFS
Chlorophyll



SeaWiFS
NDVI

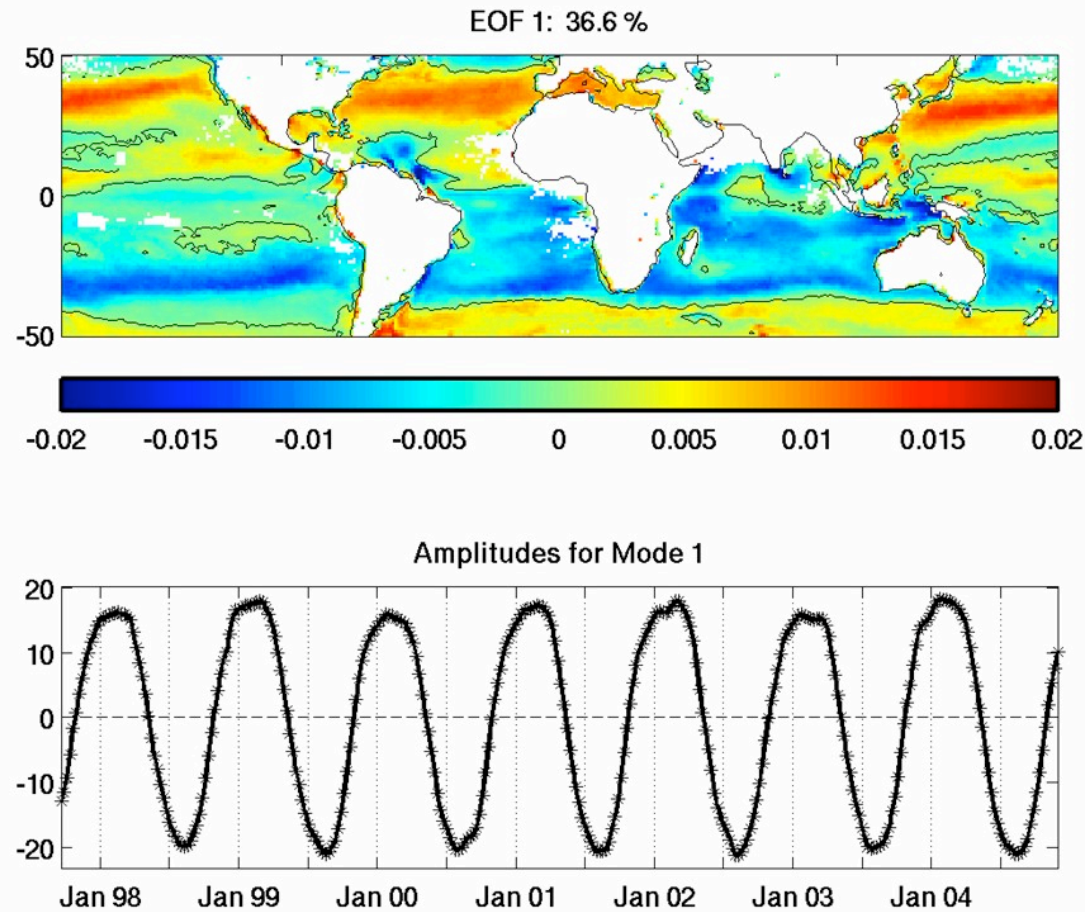
Biospheric
NPP increased
by **6 Pg**
during
transition from
1997 *El Nino*
to 1999 *La*
Nina, with
most response
in the ocean.

Behrenfeld et al. 2001, *Science*.

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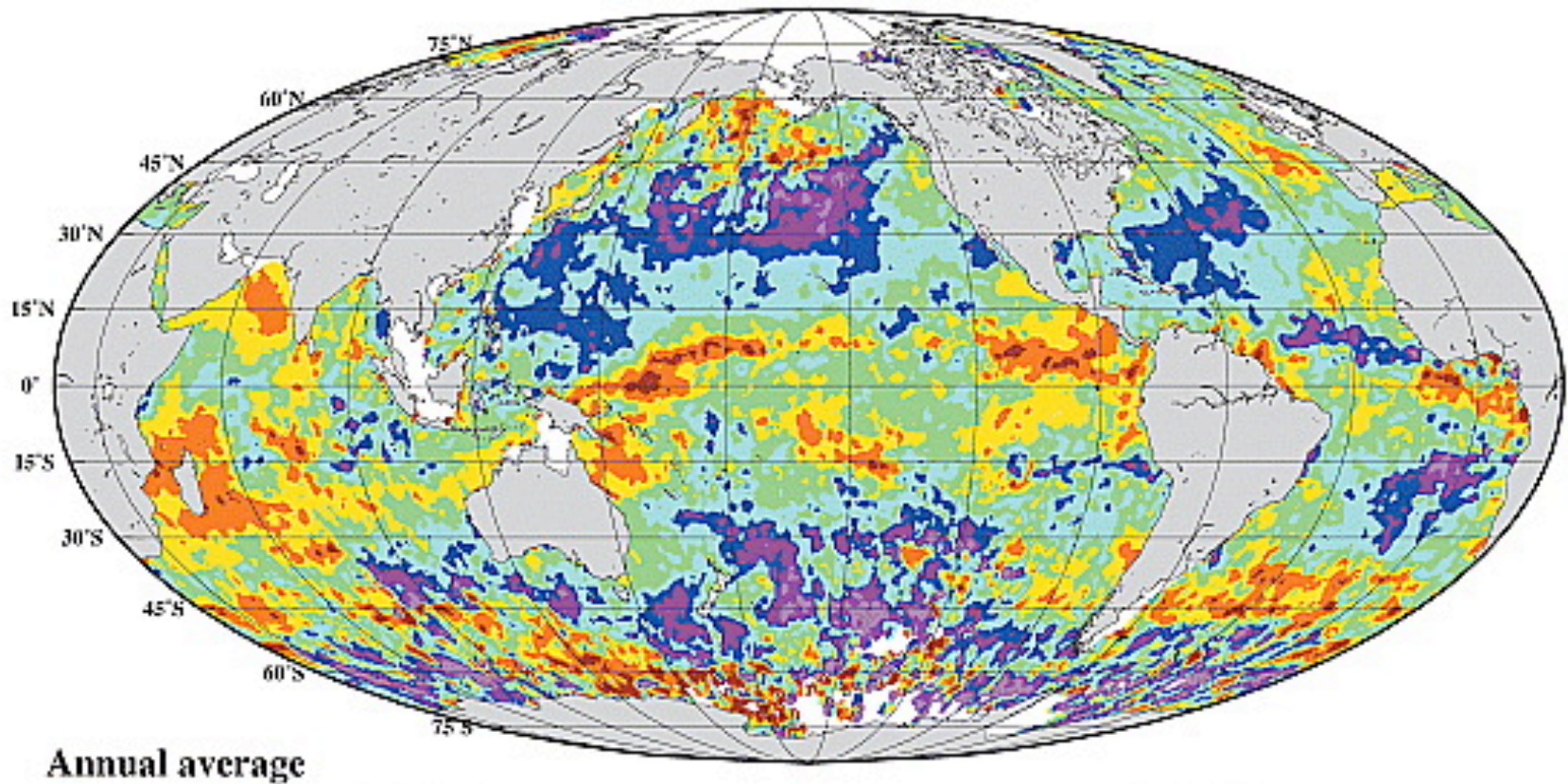
Seasonal OCR Chlorophyll Variability In the Global Ocean



From Yoder and Kennelly 2006

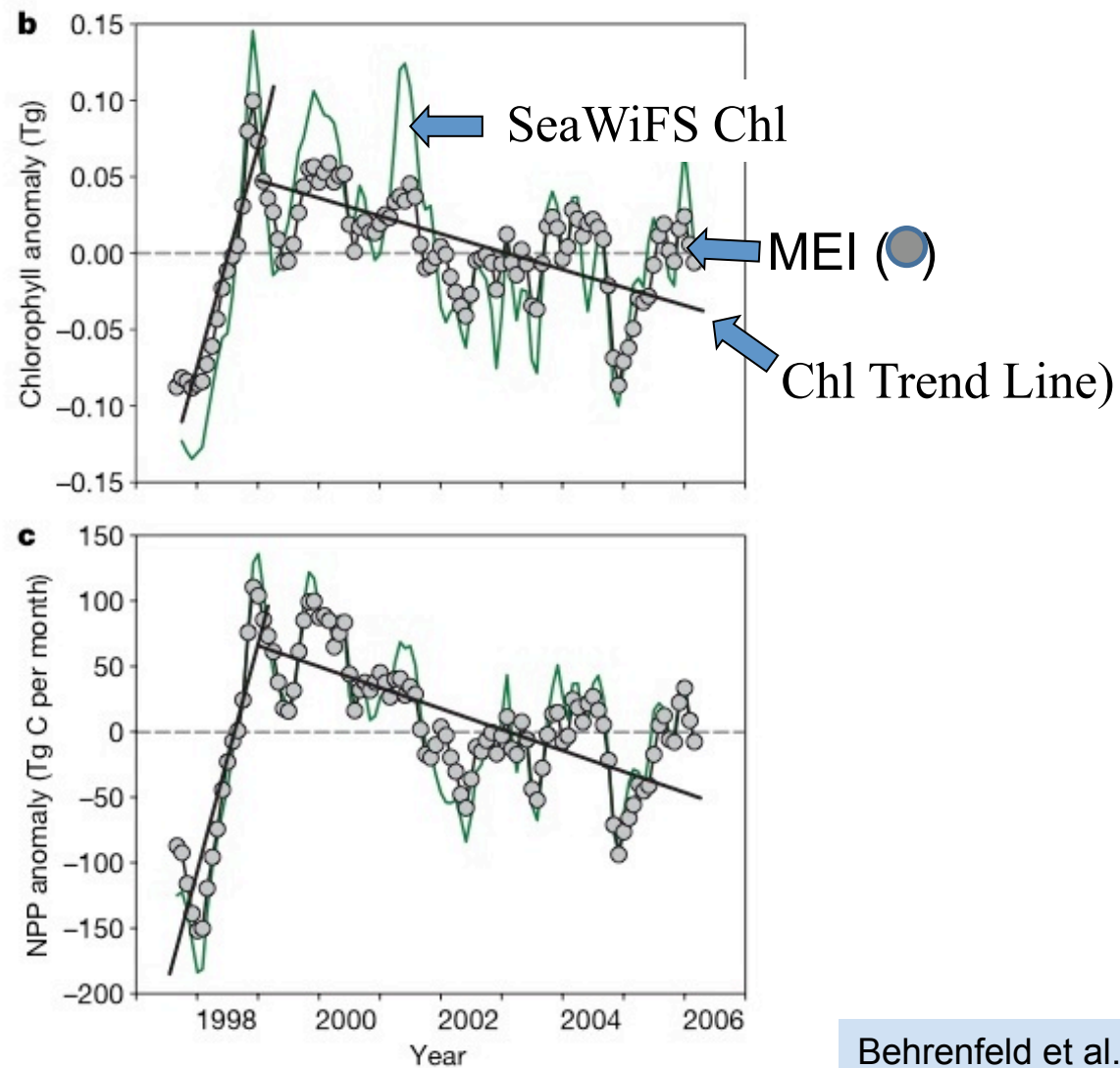
Percent Change in annual mean chlorophyll from SeaWiFS (1998-2002) to CZCS (1979-1983).

“Red” is 100% increase and “Blue” is 50% decrease



From Antoine et al. 2005

Trend in SeaWiFS chlorophyll, NPP and Stratification Anomalies (MEI) for Stratified Waters of the Global Ocean

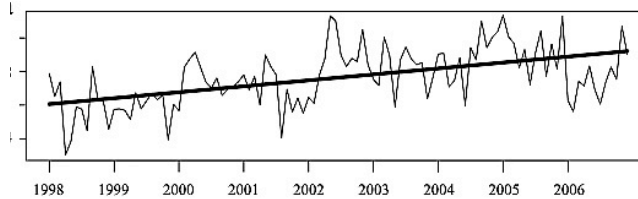


Behrenfeld et al. 2006

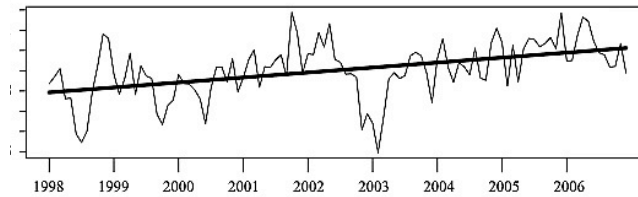
Are Areas of Ocean Waters That Have Low Biological Production Increasing?

Compare the 2 Figures. Are the Trend Lines Correct?

North Pacific

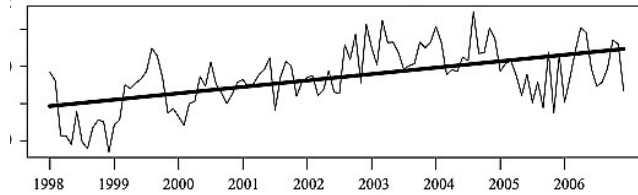


South Pacific

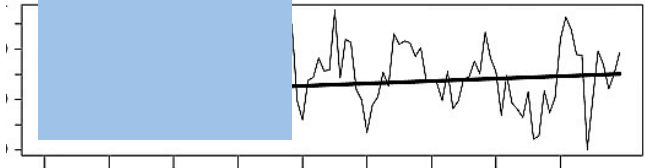
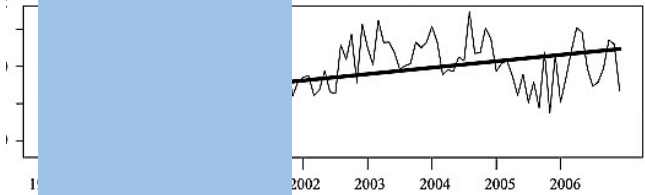
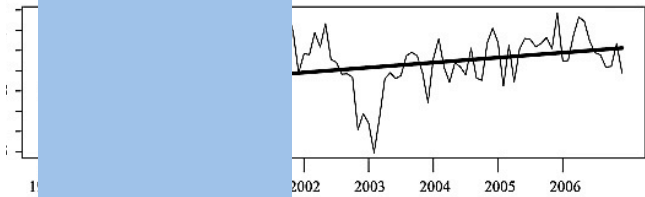
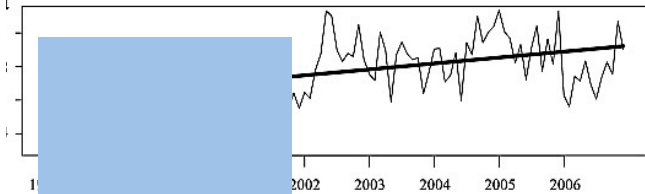
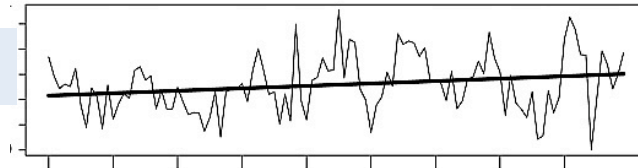


Area

North Atlantic



South Atlantic



1998

2000

2002

2004

2006

1998

2000

2002

2004

2006

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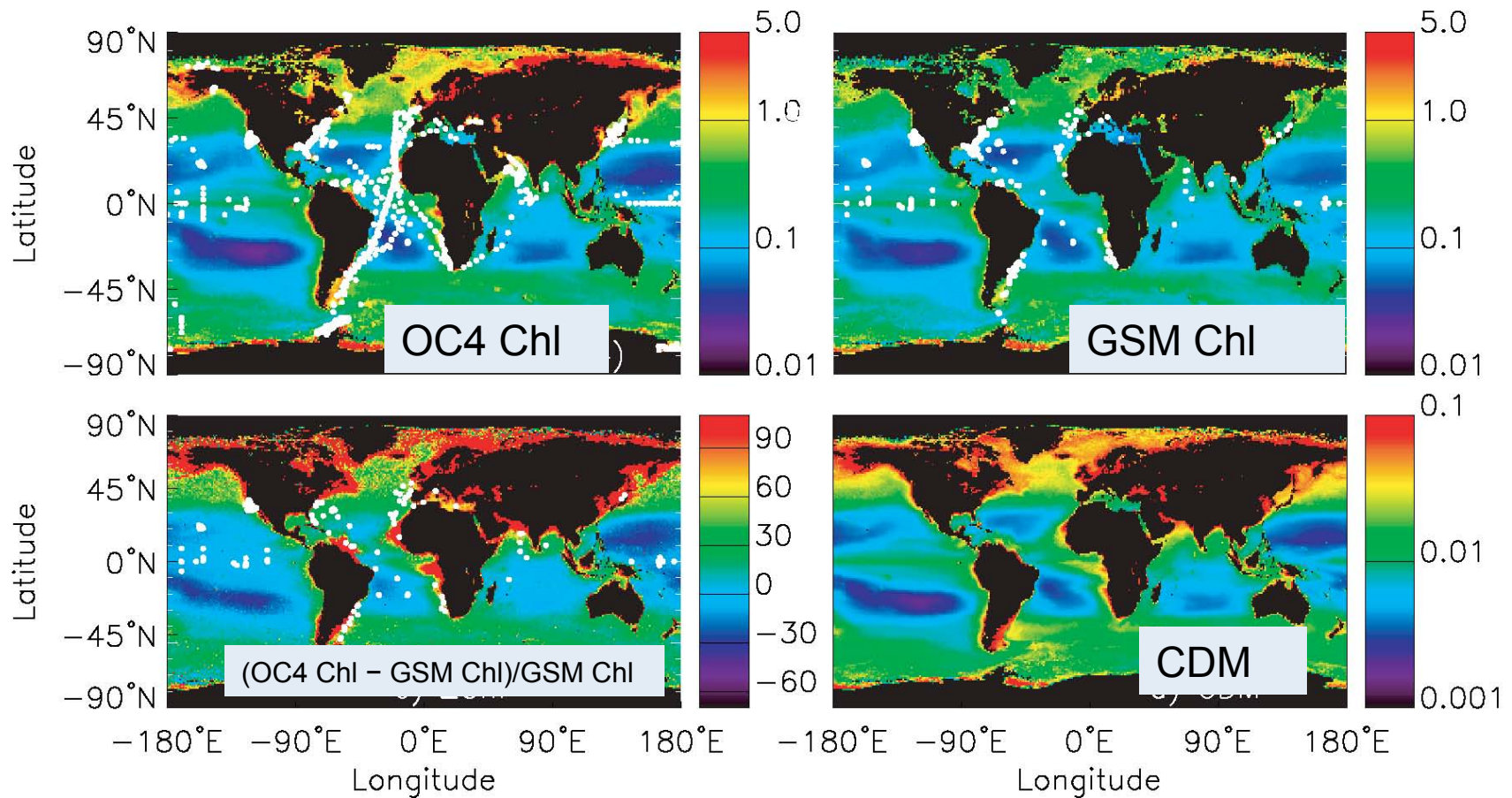
Basic Equation for Calculating Water Leaving Radiance, L_w (or Reflectance)

Garver, Siegel and Maritorena (GSM) Inversion,
where $L_w = B_b / (B_b + a)$, all as a function of λ

$$\hat{L}_{wN}(\lambda) = \frac{t F_o(\lambda)}{n_{sw}^2} \sum_{m=1}^2 g_m \cdot \left(\frac{b_{bw}(\lambda) + \underline{BBP}(\lambda_o/\lambda)^\eta}{b_{bw}(\lambda) + \underline{BBP}(\lambda_o/\lambda)^\eta + a_w(\lambda) + \frac{\underline{Chl} a_{ph}^*(\lambda)}{(1)} + \underline{CDM} \exp(-S(\lambda - \lambda_o))} \right)^m,$$

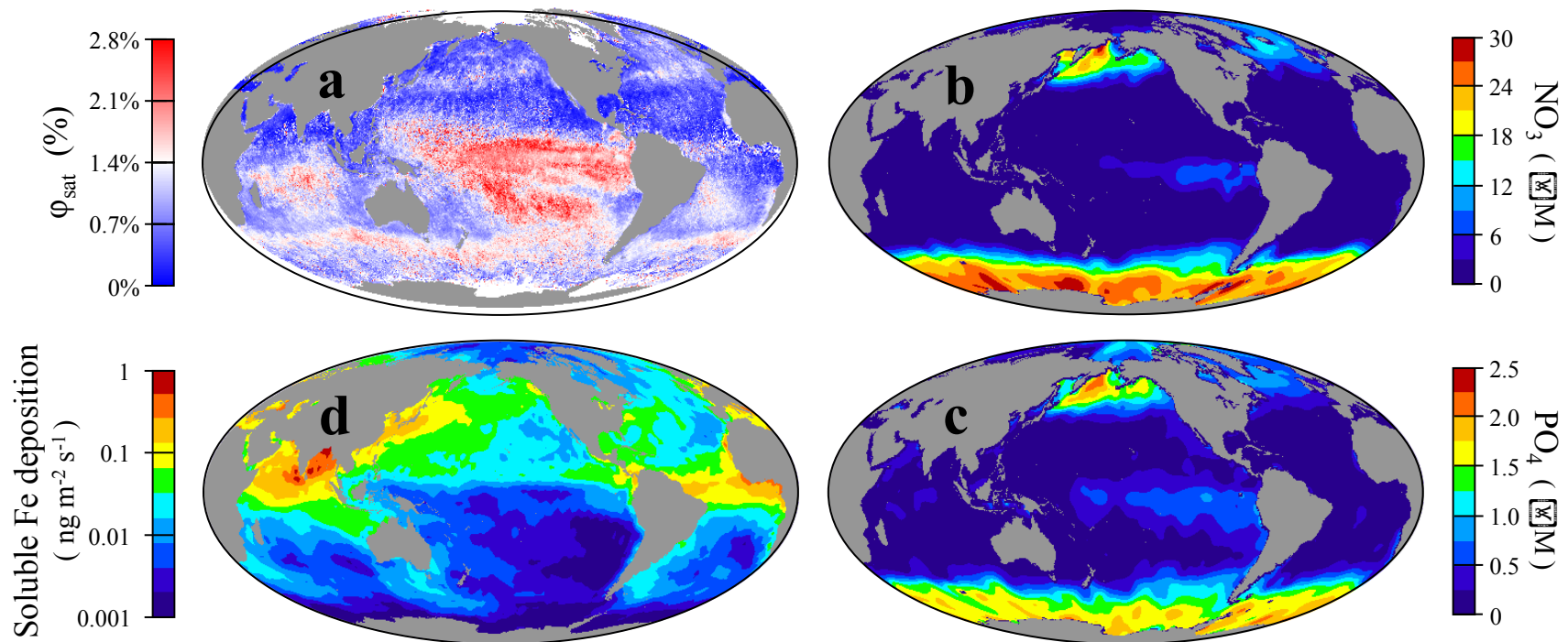
From SeaWiFS or other L_w spectra, this equation is inverted to calculate backscatter from phytoplankton particles (BBP), phytoplankton chlorophyll (Chl) and colored dissolved matter (CDM).

GSM Inversion Products



From Siegel et al. 2005

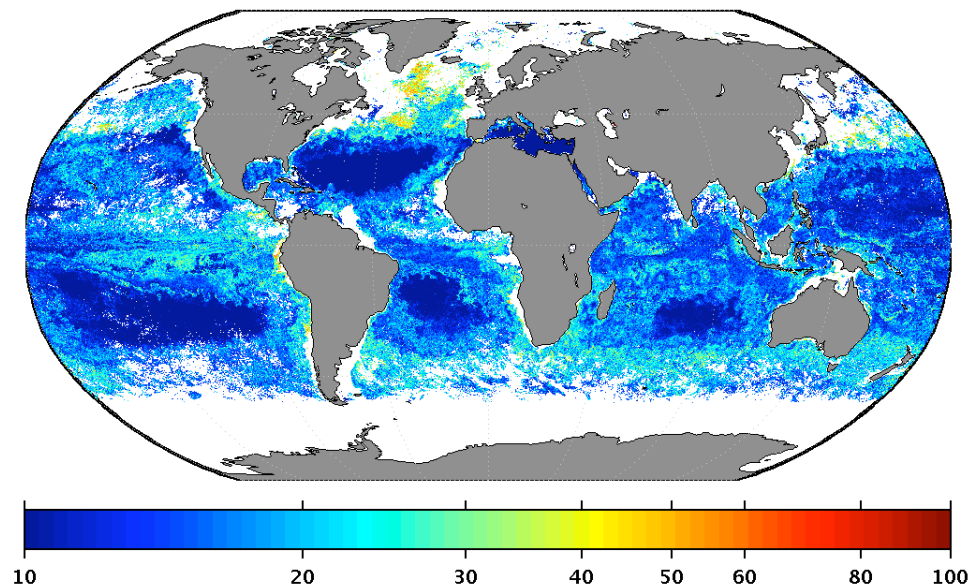
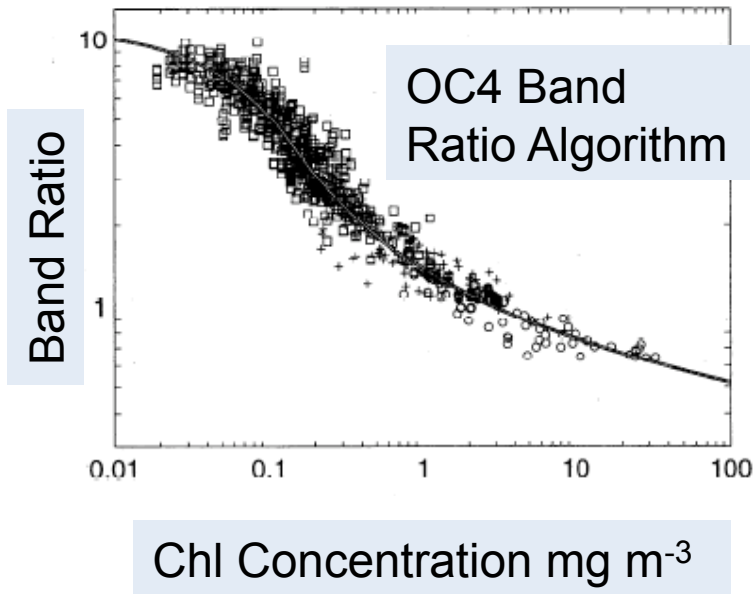
Using MODIS Measurements of Chlorophyll Fluorescence To Probe Phytoplankton Physiology from Space, e.g. Nutrient Limitation



Slide Courtesy of M. Behrenfeld

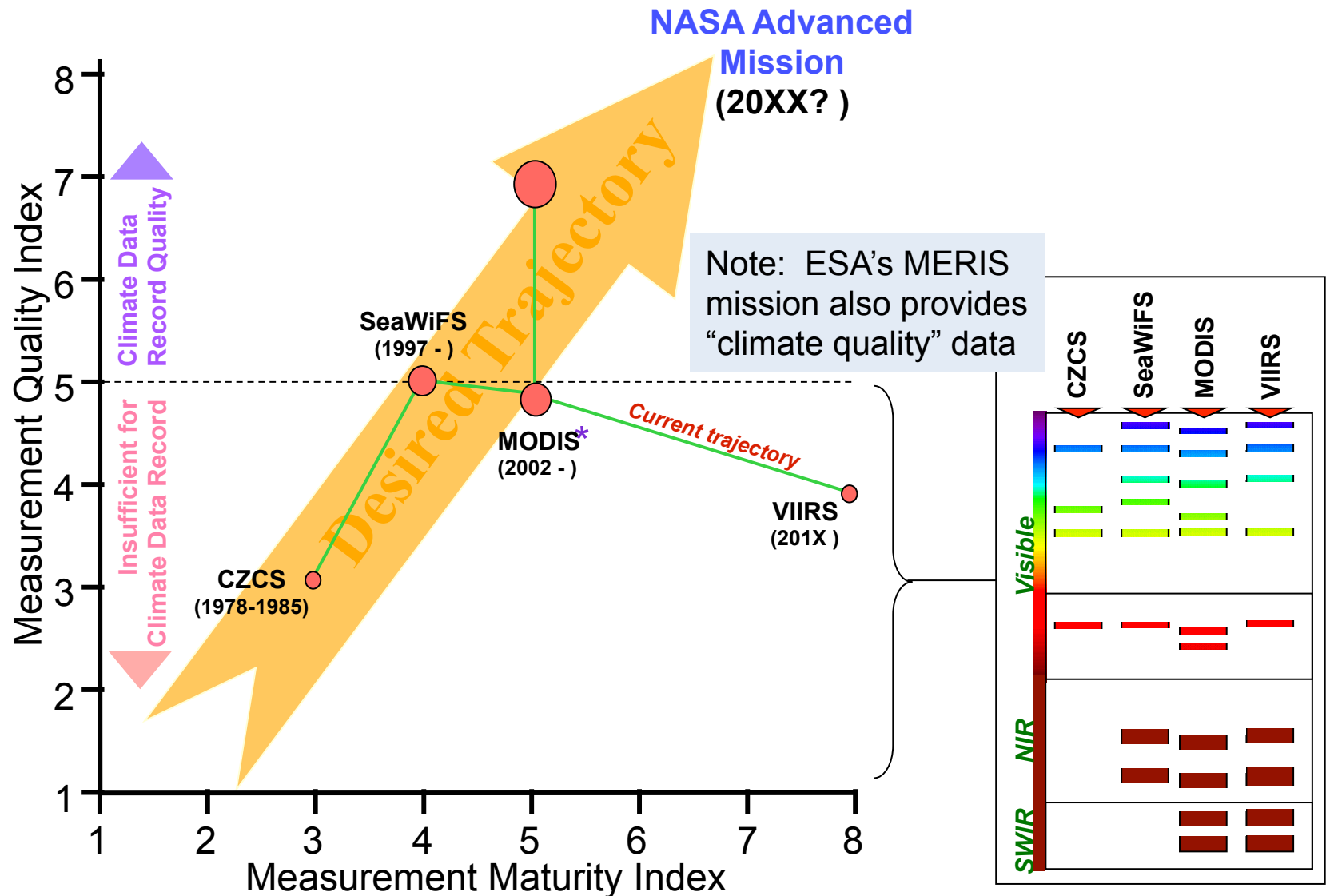
Phytoplankton Cell Size from OCR spectra – Cell Size is an Important Ecosystem Characteristics

From C. Mouw, Ph.D. Thesis, GSO-URI (2009)

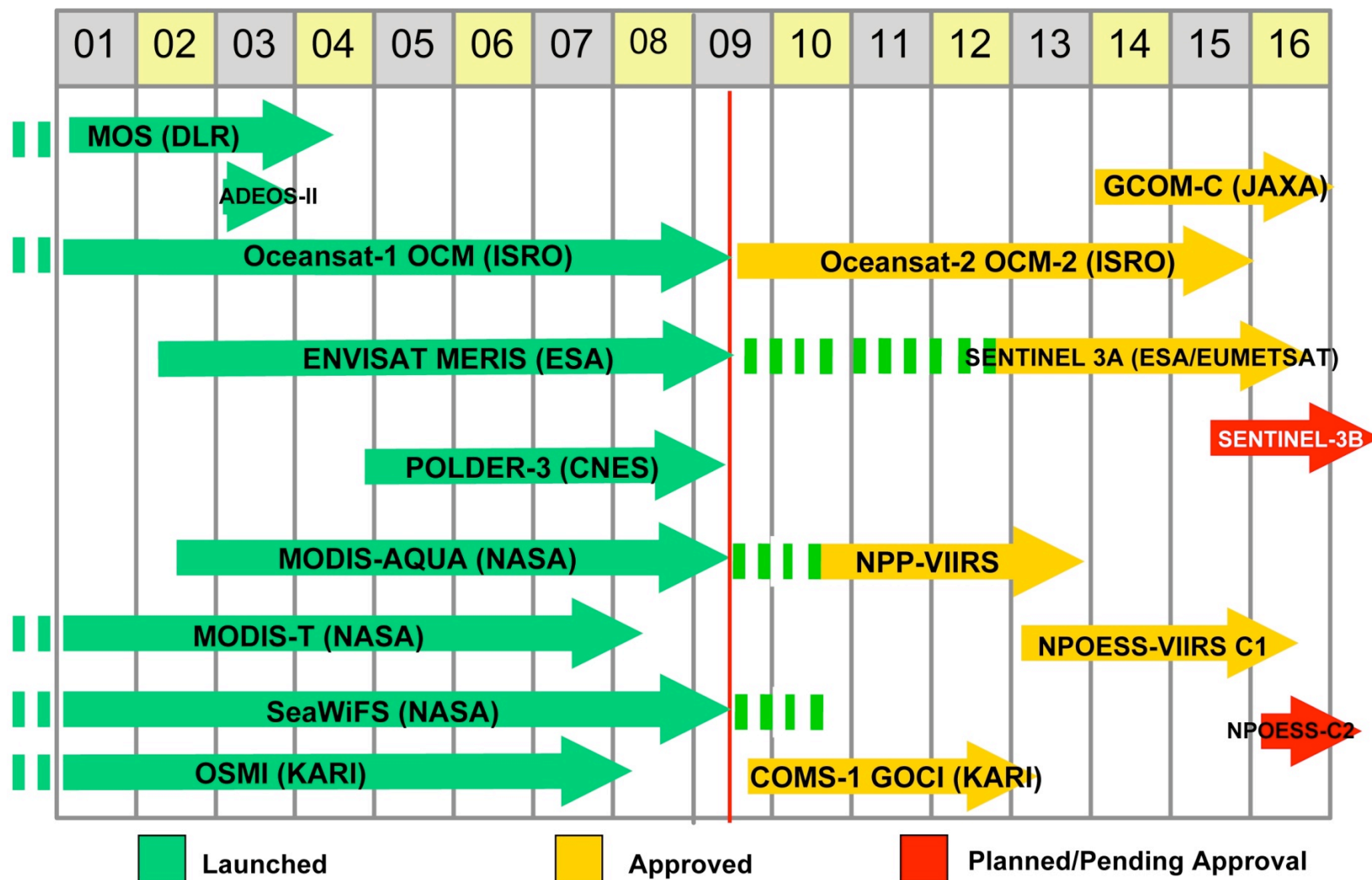


Percent Phytoplankton $>20 \mu\text{m}$, May 2006

Future U.S. OCR Missions (from M. Behrenfeld)



Ocean Colour Radiometry Missions



Conclusions – Why do we care?

Production and analysis of large-scale OCR imagery brought the ocean color community into Earth System Science in 1980s.

OCR imagery is routinely used to calculate ocean NPP at regional to global scales, and results changed our view of the productivity of the ocean component of the biosphere.

Seasonal to interannual variability in ocean productivity is now much better understood, and the imagery hints at long-term changes in ocean productivity linked to climate change.

Developing methods to quantify phytoplankton physiology and determine phytoplankton functional groups from OCR, with the potential to make significant contributions for understanding marine ecosystems.

The future of advanced, research OCR sensors is murky, but hope springs eternal.